OBSERVATIONS AND MODELS OF STAR FORMATION IN THE TIDAL FEATURES OF INTERACTING GALAXIES

John F. Wallin
Space Science Division, Naval Research Laboratory

James M. Schombert
Dept. of Astronomy, Univ. of Michigan

Curtis Struck-Marcell
Astronomy Program, Dept. of Physics, Iowa State University

ABSTRACT

Multi-color surface photometry (BVri) is presented for the tidal features in a sample of interacting galaxies. Large color variations are found between the morphological components and within the individual components. The blue colors in the primary and the tidal features are most dramatic in B-V, and not in V- i indicating that star formation instead of metallicity or age dominates the colors. Color variations between components is larger in systems shortly after interaction begins and diminishes to a very low level in systems which are merged. Photometric models for interacting systems are presented which suggest that a weak burst of star formation in the tidal features could cause the observed color distributions. Dynamical models indicate that compression occurs during the development of tidal features causing an increase in the local density by a factor of between 1.5 and 5. Assuming this density increase can be related to the star formation rate by a Schmidt law, the density increases observed in the dynamical models may be responsible for the variations in color seen in some of the interacting systems. Limitations of the dynamical models are also discussed.

INTRODUCTION

The IRAS mission has provided evidence that interaction can in some cases lead to enhanced rates of star formation in the disks of interacting galaxies (Larson and Tinsley 1978, Soifer et. al. 1987) Interaction has also been linked to nuclear activity in some studies (Hummel 1981, Bushouse 1986, Keel et al. 1985). In this paper, I wish to focus on the tidal features of interacting galaxies Because the surface brightness is fairly low (mag/arcsec^2) in these features, the rate of star formation cannot be considered large when compared to the huge bursts at the centers of some galaxies (i.e. Arp 220). However recent photometric results by Schombert, Wallin, and Struck-Marcell (1990) suggest that the rate of star formation in some tidal features must have increased during the interaction which formed them.

OBSERVATIONS

In order to gain additional information about the formation and development of tidal features, a multicolor CCD photometric study was conducted (Schombert et al. 1990) for a sample of galaxies from the Arp Atlas (1966). The surface brightness of the galaxies and their tidal features was measured in the B, V, Gunn r, and Gunn i photometric bands. The colors of the tidal features were then calculated and the distribution of colors across the systems was analysed. From these data, we concluded the following:

1. On average, about 25% of the light in these systems comes from the tidal features. Although the surface brightness is generally low, the area of these features is generally large.

2. The colors of the tidal features are generally bluer than the colors of the main galaxies. Since the colors of most of the tidal features are consistent with the colors of the outer regions of the disks they originate from, we have concluded that most of the differences in colors are due to the lower amounts of dust and younger population of star in the outer disk compared to the inner disk and bulge of the systems.

3. A few of the systems in the sample have tidal features which are very blue ($B-V<0.4$). The blue colors and knotty structure seen in these tidal features indicates that on-going star formation must be occurring in some of these systems. The result that star formation occurs in tidal features is not new. Schweizer (1978) has observed blue knots in the tails of interacting galaxies and Arp (1966) noted the "knotty" appearance of some of the tails in his atlas.

DYNAMICAL MODELS

Motivated by these observational results, simulations were conducted to understand the physical mechanisms for star formation in the outer regions of interacting galaxies. Details of the dynamical and photometric models can be found in Wallin (1989) and Wallin (1990). A restricted three body code (Toomre and Toomre 1972) is used to follow the density in co-moving regions which become part of the tidal tail. It is important to note that no hydrodynamical and self-gravitational forces are considered in these simulations. Because of this limitation, the simulations can only show where compression begins to occur due to the crossing of orbital paths in the particles. Despite this limitation, the low computational cost of the restricted three body method can allow a large number of particles to be used to increase the resolution of for the detection of density changes in small areas.

In the models, approximately 10,000 particles are initially placed in circular orbits around a softened point mass. A second softened point mass then interacts with the first as it passes in a parabolic orbit. A fixed time- step Runge-Kutta method is used as the integrator for the orbits. In order to follow the local star formation rate, regions holding approximately 0.1% of the test particles are placed in comoving orbits around the primary galaxy. As the interaction progresses, the positions of these regions are moved in the same way as the test particles. By following the number of test particles in each region as a function of time, it is possible to obtain a density history for comoving regions in the disk and tidal features. It is then assumed that the star formation rate is related to the density by a Schmidt law (Schmidt 1959).

At the beginning of the simulation, the particles are in placed circular orbits around the main galaxy. As the companion approaches and passes, a distinctive tidal tail is formed. As the companion galaxy recedes, the tidal tail grows in length and narrows at the base. A twist then develops in the tidal tail, resulting from the crossing of particle orbits in the tail. Until about 50 Myr after apoapse, the density in this region remains approximately constant. At about 80 Myr, the density increases to 350% of the original value. The timing of this density increase coincides with the passing of the twist in the tidal tail.

The density increase discussed above is a common feature of models that were run. The strength of the density increase, however, is found to depend on position of the region within the tidal tail, the inclination of the perturbing galaxy, and the mass ratio of the companion galaxy. In regions which are further from the main galaxy, the twist occurs later and in a lower density region. The compressions in the outer regions are found to be less strong than the compressions in the inner regions of the tail. As the inclination of the companion galaxy's orbit is increased, the density increase from the twist decreases. At about 30 degrees inclination, the density enhancements only occur in the inner third of the tidal tail. Although the 30 degree limit is set by the size of the region investigated in these simulations, in general, high inclination encounters increase the thickness of and decrease the compression in the tidal tails. Since the tidal tails are three dimensional features, the compression occurs only when the thickness of the tail is less then the size of the comoving regions. For non-zero inclination orbits, the thickness is greater in the outer parts of the tail than in the regions close to the disk.

PHOTOMETRIC MODELS

A broadband photometric evolutionary code was developed in order to test the effects a changing star formation rate have on the broad band colors of these regions (Wallin, 1989) . The method used is similar to that used by Larson and Tinsley (1978). In the models tested, star formation rate was initially held constant for 10 Gyr. At 10 Gyr, the star formation rate was increased. From this study, it is concluded that observationally detectable changes in the color can be seen if the star formation rate is increased by more than a factor of between two and five from the initial constant star formation rate. In terms of a Schmidt law, this change in the star formation rate indicates that a change in the local density by 200%-500% can account for the bluest colors seen in the tidal tails. This density change is consistent with the results from the dynamical models. It should be noted that the method used to understand star formation in the tidal features of interacting galaxies is similar to that of Noguchi and Ishibashi (1986). In our work, however, the local rather than global star formation was examined.

CONCLUSIONS

Although there is strong evidence that the majority of star formation during interactions takes place in the inner disks, multi-color photometry of some systems indicates that star formation occurs in the tidal features of interacting systems. In the particular case of tidal tails, this star formation may result from orbital crossings in the twist regions of tidal tails which propagate as a wave through the tail.

REFERENCES

Arp, H. C. (1966), *Atlas of Peculiar Galaxies*, (Pasadena : California Institute of Technology).

Bushouse, H. A. (1986), *A. J.*, **91**, 255.

Hummel, E. (1981), *Astron. Astrophys.*, **96**, 111.

Keel, W. C., Kennicutt, R. C. Jr., Hummel, E., and van der Hulst, J. M. (1985), *A. J.*, **90**, 708.

Larson, R. B. and Tinsley, B. M. (1978), *Ap. J.*, **219**, 46.

Noguchi, M. and Ishibashi, S. (1986), *M. N. R. A. S.*, **219**, 305.

Schmidt, M. (1959), *Ap. J.*, **129**, 243.

Schombert, J. M., Wallin, J. F., and Struck-Marcell, C. (1990), *to be appear in A. J.*

Schweizer, F. (1978), *in Structure and Properties of Nearby Galaxies*, eds. Berkhuijsen, E. M. and Wielebinski, R. (Dordrecht : D. Reidel) p. 279.

Soifer, B.T., Houck, J. R., and Neugebauer, G. 1987, *Annual Reviews of Astronomy and* Astrophysics 25, ed. G. Burbridge, D. Layzer, J. G. Phillips, p. 187.

Toomre, A. and Toomre, J. (1972), *Ap. J.*, **178**, 623.

Wallin, J. F. (1989), *Dynamical and Photometric Evolutionary Models of Tidal Tails and* Shells, Ph.D. Thesis, Iowa State University.

Wallin, J. F. (1990), *Dynamical and Photometric Evolutionary Models of Tidal Tails*, to be submitted to A. J.

DISCUSSION

Kennicutt: What is the typical dynamical age of your blue tidal features?

Wallin: Since we don't have velocity information or detailed models for all the galaxies we observed, it is difficult to give an exact answer. The blue tails seem to be in systems which are in the early stages of interaction. In most cases, these are tidal bridges between the galaxies.

Bushouse: Have you compared the colors of the tidal tails with the outer disk regions, as opposed to the integrated colors of the whole galaxy? If the colors of the tails and the outer disk are similar, then it should indicate that the tails are made up of stars that have been stripped from the outer disk.

Wallin: In most cases, the colors of the tails are very similar to the colors of the outer disk. In some cases, however, the colors of the tidal features are bluer than the colors of the outer regions indicating local star formation.

Zasov: Did you compare the colors of galaxies and their tidal features on a color-magnitude diagram? Are there any differences between their color excesses? A difference may take place if there is a redistribution of the interstellar medium due to the interaction.

Wallin: We did examine color-magnitude diagrams of regions in the tail and across systems. It is impossible to examine the changes in reddening since the surface brightness varies between regions.